45th AIAA Aerospace Sciences Meeting and Exhibit
8 - 11 January 2007, Reno, Nevada

AIAA 2007-543

Exercise Countermeasures and a New Ground-Based Partial-g Analog for Exploration

Gail P. Perusek[1], Beth Lewandowski[2], Kelly Gilkey[3], and Marsha Nall[4]
NASA John H. Glenn Research Center, Cleveland, Ohio, 44135

Marcus L. Just[5]
Zin Technologies, Brookpark, Ohio, 44135

Peter R. Cavanagh[6], Matthew Kuklis[7], and Sara Novotny[8]
Center for Space Medicine, Cleveland Clinic, Cleveland, Ohio, 44195

and

John K. DeWitt[9]
Bergaila Engineering Services, Houston, Texas, 77077

The enhanced Zero-gravity Locomotion Simulator (eZLS) at NASA Glenn Research Center is described and summary data from a pilot research study comparing comfort and pressure data from two different International Space Station crew exercise harness designs are presented. This new ground-based simulation capability was developed to help address the detrimental physiological effects of spaceflight on the musculoskeletal system through improved exercise countermeasures systems, and to evaluate exercise countermeasures devices and prescriptions for space exploration. Aside from space applications, experiments conducted using the eZLS may help medical researchers develop insights into the role of exercise in the prevention of osteoporosis in the terrestrial population since the mechanism of bone and muscle loss is very similar, though greatly accelerated during space travel. The eZLS will be used as a ground-based testbed to support future missions for Space Exploration, and will eventually be used to simulate planetary locomotion in partial gravity environments including the Moon and Mars.

Nomenclature

T	=	total tension in supports
Fr	=	friction force
M	=	mass of test subject
ge	=	gravitational constant on earth
gl	=	lunar gravitational constant
μ	=	coefficient of friction

[1] Project Manager for Exercise Countermeasures, Human Research Office, 21000 Brookpark Road/Mail Stop 86-13.
[2] Biomedical Engineer, 21000 Brookpark Road/Code RUB/ Mail Stop 110-3.
[3] Aerospace Engineer, 21000 Brookpark Road/Code DEV/Mail Stop 86-13.
[4] Program Manager, Human Research Office, 21000 Brookpark Road/Mail Stop 77-5.
[5] Project Technical Lead, Exploration Human Research, 2001 Aerospace Parkway, Mail Stop 2K1/Zin Chairman,
[6] Chairman, Department of Biomedical Engineering, Lerner Research Institute, Mail Code ND-20.
[7] Senior Research Engineer, Department of Biomedical Engineering, Lerner Research Institute, Mail Code ND-20.
[8] Senior Research Engineer, Department of Biomedical Engineering, Lerner Research Institute, Mail Code ND-20.
[9] Senior Biomechanist, 2101 NASA Parkway, Mail Stop JSC:SK.

I. Introduction

THE NASA Glenn Research Center, in collaboration with The Cleveland Clinic, Zin Technologies, and NASA Johnson Space Center, has developed a new ground-based simulator to address the need for simulating in-flight (microgravity) and surface (partial-gravity) exercise to advance the health and safety of astronaut crews and the next generation of space explorers. The Exercise Countermeasures Laboratory features an enhanced Zero-gravity Locomotion Simulator (eZLS), designed to allow development and validation of advanced exercise countermeasure devices, requirements, and exercise prescriptions for mitigating the detrimental physiological effects of long-duration spaceflight.

Muscles and bones weaken as an adaptation to the zero gravity environment experienced during spaceflight. To date, no exercise regimen has been effective in mitigating these changes in crewmembers. In an effort to help develop improved exercise routines and equipment for crew members, the Exercise Countermeasures Project at NASA Glenn Research Center developed the eZLS to provide a test bed for conducting research with human participants in research areas including understanding metabolic cost of locomotion in partial gravity, improving crew comfort during exercise, exercise prescription and hardware optimization based on directly-measured mechanical dose to the musculoskeletal system, and developing and characterizing advanced exercise device concepts for Exploration class missions.

A B

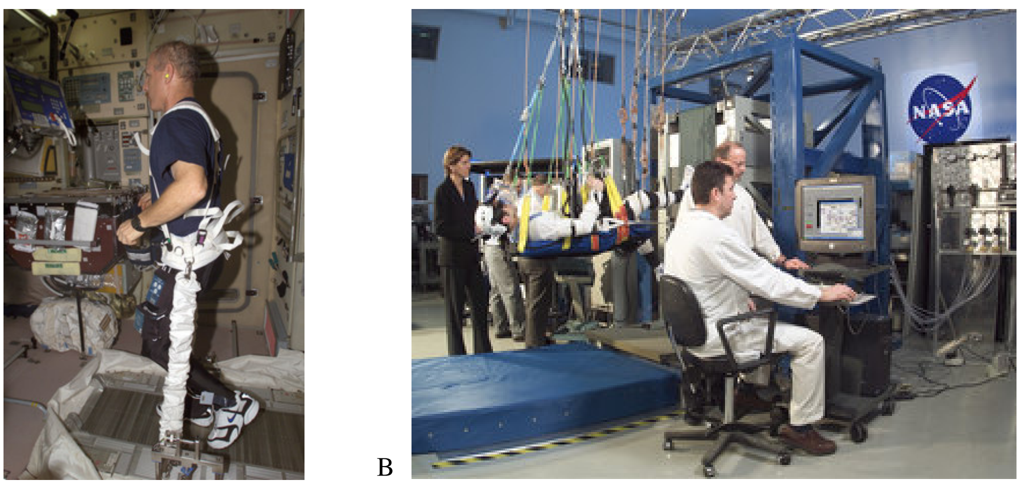


Figure 1a. On-Orbit Treadmill (at left) and Ground Simulation of Treadmill Locomotion (at right). *(A) International Space Station (ISS) Treadmill with Vibration Isolation and Stabilization (TVIS) in use during exercise session. (B) The enhanced Zero-g Locomotion Simulator (eZLS) in the Exercise Countermeasures Laboratory (ECL) at NASA Glenn Research Center during test operations.*

The eZLS is the latest generation of the device that was originally developed by Davis, et al.[1] The current version features an offloading suspension system to support a test subject in a supine position as seen in Figure 1a (B), and a vertical treadmill that is also offloaded by virtue of an air bearing table. The treadmill floats on a set of 8 air bearings (New Way Air Bearings, Aston, PA) to allow a 1 degree-of-freedom frictionless translation of the treadmill rack or exercise device during use. The treadmill interfaces to a force reaction frame via a set of four custom made variably-compliant isolators (Fig. 1b). The isolators can be configured to simulate compliant interfaces to the vehicle, which will affect mechanical loading to crewmembers during exercise. Mechanical loading is thought to be an important stimulus in the maintenance of bone and muscle, and characterizing this loading (e.g., rate, magnitude, frequency) is a crucial part of understanding the 'dose' of mechanical stimulus in order to optimize devices and prescriptions for use in space applications.

The subject suspension system simulates a reduced gravity environment by completely or partially offloading the weight of the exercising test subject's head, torso, arms, and legs. The test subject is suspended from a free-standing truss superstructure which stands 6.1 m (20 ft.) from ground level. The subject can be suspended horizontally for zero-gravity simulations, or at the appropriate pitch angle for partial gravity simulations. The suspension system uses remote-operated motors which allow for adjustment of tension in the suspension bungees, which support the test subject, and speeds the setup operation time. The subject's body weight relative to the treadmill, or gravity-replacement force, is then controlled via a motorized subject load device, referred to as the Linear Motor Subject Load Device (LM-SLD), described further in Section IB. The LM-SLD, which is set and verified for subject safety prior to each session, employs a force-feedback closed-loop control system to provide a relatively constant force to the test subject during locomotion.

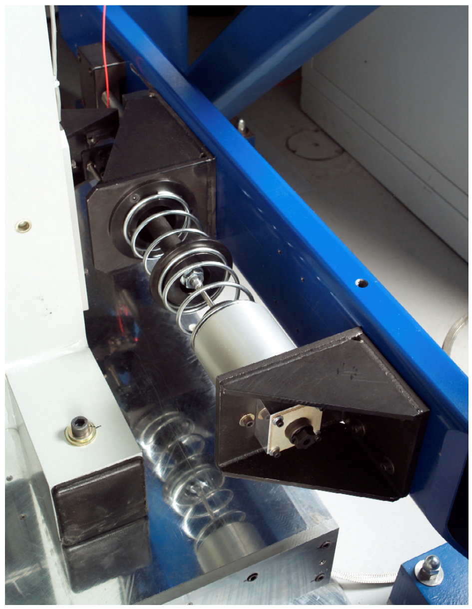


Figure 1b. Variably-compliant isolator. *The enhanced Zero-g Locomotion Simulator (eZLS) variably-compliant isolators (4 total) mount between the treadmill rack and the ground reaction frame, providing variable and controllable interface compliance between the exercise device and simulated vehicle which, when used with the treadmill air bearing system, can mimic the on-orbit interface dynamics in 1 degree-of-freedom. The isolators use passive adjustable air dampers and spring sets that can be changed out to obtain various spring-damping ratios.*

A. Simulating Lunar Gravity with the eZLS

In addition to a supine suspension and vertical treadmill configuration for zero-gravity simulations, the entire assembly can be pitched at the appropriate angle to simulate partial gravity, e.g., lunar gravity. While locomotion on a pitched surface has been used as a standard means of reducing the effective gravity component on the longitudinal axis of the body, the suspension method has historically been executed in a sideways manner as was done during the Apollo era[2]. To the best of our knowledge, the eZLS is the only lunar gravity locomotion simulator that employs a supine suspension approach and a pitched treadmill. Attempts at sideways suspension introduced added restrictions on the test subject's locomotion of their extremities closest to the ground. Support of all four limbs was not distributed evenly and the test subject needed to exert excessive energy to overcome the unbalanced support system. In contrast, methods employing supine (face up) suspension methods for zero-gravity locomotion simulation allow even support of all extremities. The eZLS supine suspension system is based largely on the Cleveland Clinic's Zero-gravity Locomotion Simulator (ZLS) suspension system[1,3]. However, unlike the ZLS, lunar gravity simulation can be implemented in the eZLS by pitching the treadmill rack (Fig. 2a), and adjusting the subject suspension system forward to accommodate the angle. We refer to lunar gravity as 1/6th that of earth's gravity. In reality lunar gravity is closer to (1.62 / 9.806) that of earth's gravity. For calculations we use the more precise fraction, while for simplicity we show "1/6th-gravity."

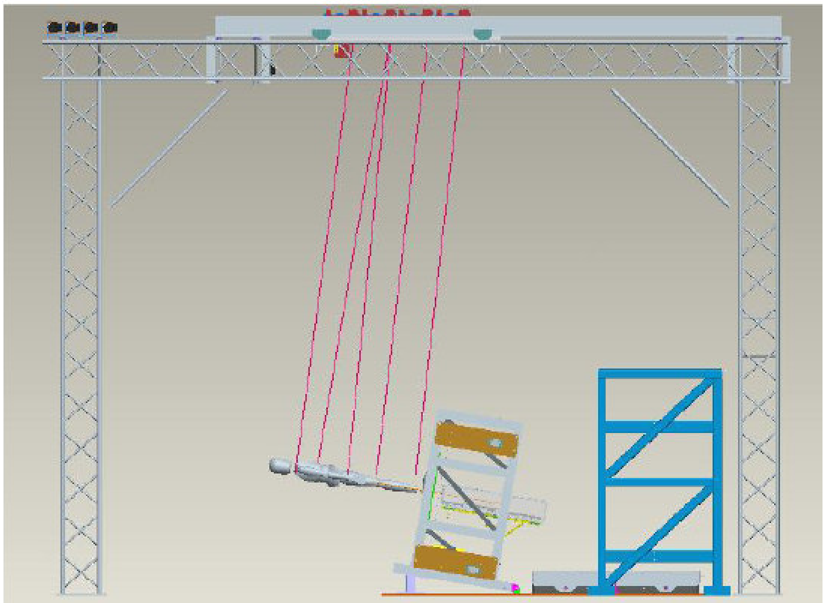


Figure 2a. Configuration for lunar gravity simulation. *Schematic of lunar gravity configuration (1/6th-gravity on the subject's feet) with pitched suspension system and treadmill at 9.5 degrees from vertical.*

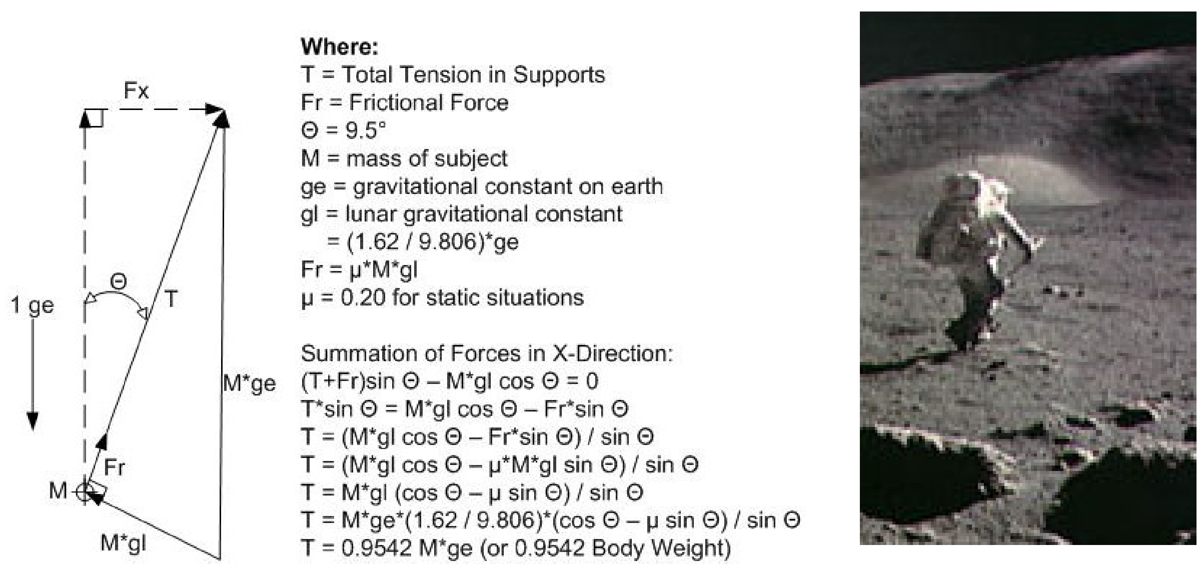


Figure 2b. Calculating the vectors for a lunar gravity equivalent force on earth. (A) *Free-body diagram showing force vectors and their angles which provide the geometric equivalent of a lunar gravity vector on earth and the resultant tension in the suspension system.(B) Apollo 17 astronaut on the moon.*

The pitch angle of 9.5 degrees from vertical allows 1/6th of the test subject's weight to be applied to the treadmill surface or exercise device against which the subject rests. The suspension system bungees and support cradle, also pitched at 9.5 degrees, carry the balance of the body weight and offload all but the 1/6th gravity vector acting along the subject's longitudinal axis.

Aside from pitching the subject suspension system and treadmill for lunar gravity, other pitch angles can be achieved for varying gravity loads (e.g., Mars gravity). Further, the LM-SLD system can be set to any gravity-replacement load as well, for example, to simulate exercise on a lunar treadmill with a subject load device in place.

B. Constant-Force Subject Load Devices (SLDs)

We developed two ground-based SLDs for use in the enhanced Zero-gravity Locomotion Simulator (eZLS) and the Cleveland Clinic Zero-gravity Locomotion Simulator (ZLS) which use different technologies, and which were designed to allow variable gravity replacement load settings, while keeping the force applied to the test subject nearly constant throughout locomotion once they are set.

The first constant-force SLD utilizes two linear servo motors (Trilogy Systems Corp., Houston, TX) with 45.7 cm (18 in.) stroke length and which are controlled by a closed-loop force-feedback proportional-integral control. This Linear Motor Subject Load Device, or LM-SLD (Fig. 3a), uses two in-line force transducers to provide force feedback to the control system and a response measurement for measuring load directly on the LM-SLD to the subject harness.

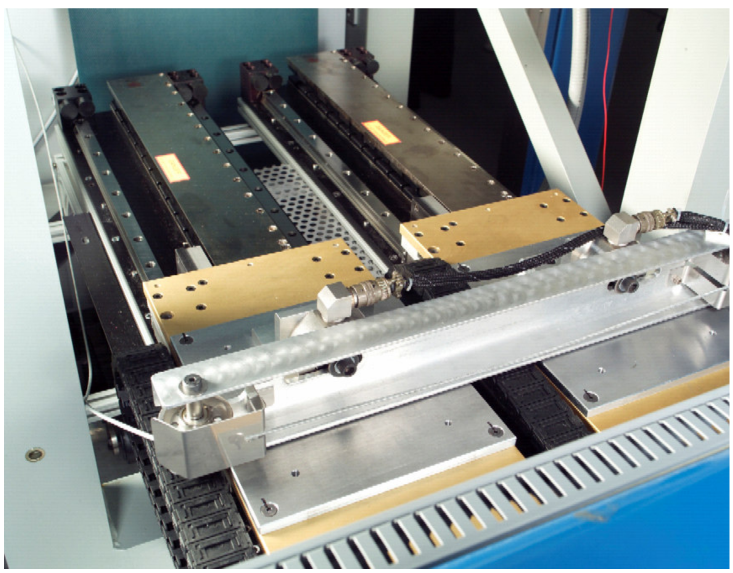
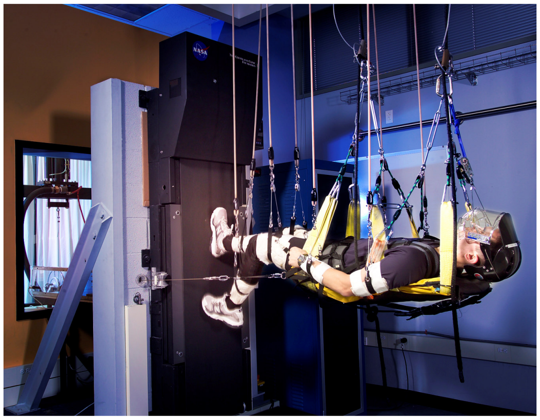


Figure 3a. Linear Motor Subject Load Device (LM-SLD). *Developed for the NASA Glenn Exercise Countermeasures Laboratory, uses two load cells for force-feedback to a closed-loop control system to keep force nearly constant on the exercising test subject.*

The second constant-force SLD is based on a passive pneumatic suspension device (CSA Engineering Inc., Mountain View, CA), an accumulator tank, and a regulator. This pneumatic subject load device, or P-SLD (Fig. 3b), uses a single pneumatic cylinder with 2.7 kN (600 lb. force rating) to provide a nearly constant spring force on the cables attached to the subject harness. The spring rate of the cylinder is 0.18 – 0.36 N/cm (0.1-0.2 lbf/in.). An attractive feature of this device is that it is a passive device which requires no electrical power input or feedback control. The device does require a regulated source of dry, filtered, compressed air supply at 552 kPa (shop air at ~80 psig), which is supplied to the cylinder via a 0.26 m^3 (60 gal.) accumulator tank.

A



B

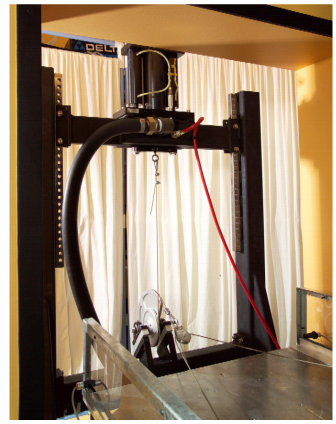


Figure 3b. Cleveland Clinic Zero-g Locomotion Simulator (ZLS) and Pneumatic Subject Load Device (P-SLD). *(A) The pneumatic cylinder is located behind the vertical treadmill and can be seen at far left. (B) The cables from the test subject harness pass through spool-shaped guide pulleys near the treadmill belt and are gathered to a single cable and passed over a displacement multiplier cam which directs the cable up to the pneumatic cylinder. The accumulator tank, air filter, and regulator panel are not visible.*

The LM-SLD and P-SLD are not used together but rather serve as dissimilar redundant systems for the ground-based simulators, which can use Series Bungee System (SBS) bungees as back-up SLDs, as is done on the Treadmill with Vibration Isolation and Stabilization (TVIS) treadmill on the International Space Station.

We believe that a constant-force gravity-replacement mechanism will improve the efficacy, and also possibly comfort, during exercise, thus improving crew compliance to exercise prescriptions and enabling the required mechanical stimulus to the musculoskeletal system to be achieved for optimal crew health. Further, the number of test subjects who will be involved in studies utilizing the simulators will exceed those of crew members using the TVIS SLD system on-orbit. As such, we seek to understand and improve comfort for the ground-based simulators as well.

C. Non-constant force subject loading -- Series Bungee System (SBS) bungees

A Series Bungee System (SBS) (Fig. 3c) was provided by NASA Johnson Space Center/Wyle Laboratories for use in the harness comfort pilot study described herein. These SBS bungees interface between the subject exercise harness, also seen in Fig. 1a (A), and eye bolts outboard of the treadmill belt (right and left sides). The load setting is adjustable by adding or removing bungee clips to change the initial length of the SBS bungee assembly. For the ground studies in eZLS, the initial load setting is established by the force reading on the force plate (Kistler Corp., Amherst, NY) mounted beneath the treadmill belt with the test subject standing quietly wearing the SBS bungee and harness assembly while suspended in the eZLS. The SBS bungees have a stiffness of 5.25 to 7 N/cm (3 to 4 lb/in.) after a stretch of about 13 cm (about 5 inches) from resting initial length (i.e., in their operational range).

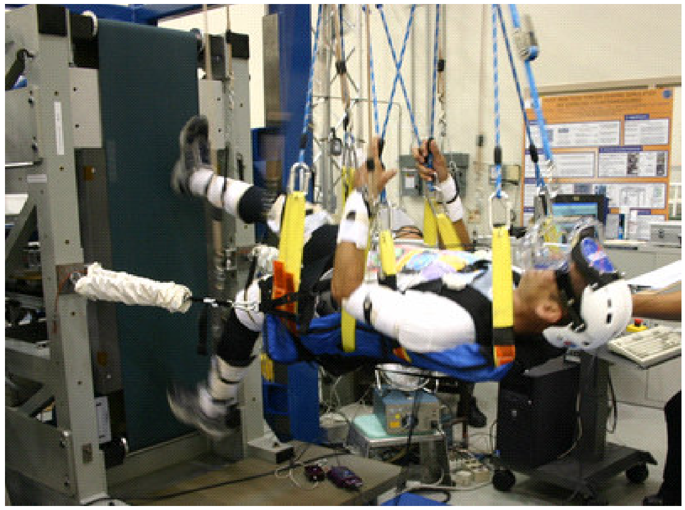


Figure 3c. Series Bungee System (SBS) bungees. *Used as a subject loading device during treadmill exercise on the International Space Station, the SBS bungee (on left side of subject) is here shown in use in the enhanced Zero-g Locomotion Simulator.*

II. Computational Modeling

The enhanced Zero-g Locomotion Simulator (eZLS) includes the ability to mimic the variable interface dynamics as found on the International Space Station (ISS), to simulate interface dynamics of other vehicles, or to simulate terrestrial interfaces by completely grounding or "locking out" the isolators between the treadmill (or exercise device) and the ground reaction frame. It is important to mimic variable interface configurations as seen on the ISS and other possible vehicle carriers to gain insight into how these interfaces may affect musculoskeletal loading and the resultant efficacy of the countermeasure. Peak magnitude and rate-of-change of force (F and dF/dt, respectively) elicited under the feet are widely believed to be important criteria for the efficacy of these countermeasures against loss of bone mass. However, there is no information in the literature to demonstrate what F and dF/dt values are imposed on the lower extremities during exercise throughout the range of available gravity-replacement loads imposed on the subject during exercise on the ISS, where the exercise devices interface to the vehicle in various ways – from a completely mechanically decoupled interface, as with the TVIS treadmill, to a compliant mechanical interface, to a hard-mounted mechanical interface. It is shown herein that these various isolation schemes affect the F and dF/dt delivered to the crewmember.

The reduction of reactive forces introduced by necessary vibration isolation systems is suspected in causing the workout to be less effective in providing mechanical stimulus to the musculoskeletal system, thus contributing to bone and muscle loss in space. Vibration isolators are needed at the exercise system interface to the space vehicle to attenuate forces that are transmitted into the vehicle. A dynamic model of the eZLS was created to understand system dynamics and their effect on foot reaction forces between the crewmember and the exercise countermeasure device. One of the goals of the project is to demonstrate the effect of isolators with different properties on foot reaction forces, for treadmill devices and advanced exercise countermeasures concepts as they emerge.

For the computational simulation, the exercise system was defined to have six distinct elements (see Fig. 4).The model aimed to simulate rigid body dynamics of the treadmill and its supporting frame or "rack" (items 3 and 4 in Fig. 4) as the simulated crewmember foot forces (element 1) excite the dynamics of the isolator components (element 5). The isolators were assumed to be grounded (at element 6), as opposed to being interfaced to ISS as depicted in Fig. 4. Foot forces were approximated to be a sinusoidal, displacement-driven body load into the crewmember's legs.

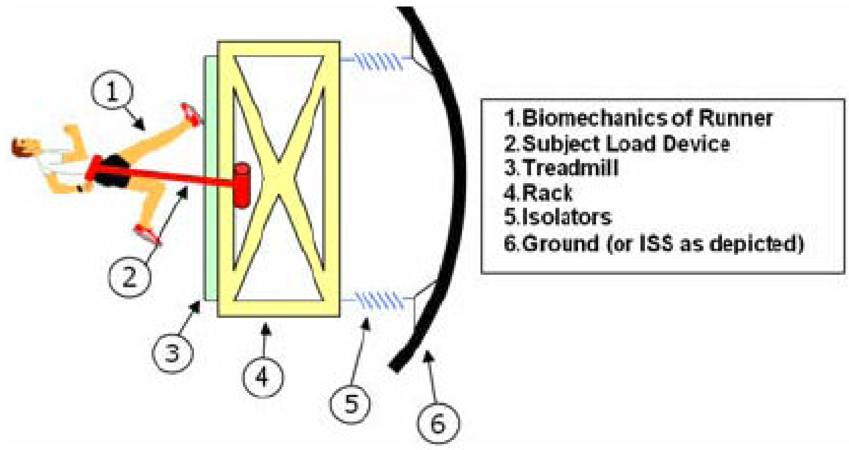


Figure 4. Schematic of Dynamic Model of Runner, Treadmill, and Vehicle.

Leg stiffness and damping values were chosen to obtain foot force input loads of 2.5 times body weight (BW) peak force into solid ground[4]. The cadence was set to a frequency of 3 Hz. The input signal was half-wave rectified since the foot force could only be directed into the treadmill surface. The treadmill and rack were modeled as a rigid body, the position of which was subtracted from the displacement driven runner load. Isolator stiffness and damping properties were calculated so that certain desired resonances could be examined. Since the position of the treadmill was driven by the simulated crewmember (runner), depending on isolator stiffness and damping, the treadmill surface tended to dynamically yield against the footfalls. Output from the model was treadmill deflection and foot reaction forces.

The model was used to gauge the potential effect that various isolator designs may have on foot reaction forces. Four simulated isolators were set to resonances of 1 Hz, 3 Hz, 10 Hz, and 25 Hz, with the last case being a baseline case representing a nearly hard-mounted configuration. The 1 Hz isolator set naturally produced the best attenuation of forces transmitted into the ground, however at the expense of 8.7% less total foot reaction force compared to the baseline 25 Hz case. While the 1 Hz case peak forces only dropped by about 4.7%, the sum of the forces increased in a non-linear fashion. Also, the model showed that a 3 Hz isolator resonance will couple with the gait cadence frequency and cause many undesirable effects such as amplified ground interface forces and treadmill oscillations, and a 43.5% reduction in summed foot reaction forces.

To allow interface forces between the exercise device and the runner to be accurately measured, non rigid-body structural modes of the eZLS testbed components were analyzed using finite element analysis to ensure that the forcing function induced by the subject and subject load device are decoupled from non-rigid body modes of the simulator. Components of the simulator that were modeled included (i) the inertial ground frame reference, or ground reaction frame, (ii) the treadmill exercise device, and (iii) the 1-Degree of Freedom offloading and translation system (air bearing table) for the exercise device. Target modes were set at 1.7 times the highest bandwidth of interest in the ground reaction force Z-axis component. The Z-axis was oriented normal to the running surface. Frequency content of human ground reaction force has been shown to be below 25Hz[5]. Acceptable non-rigid body structural modes were established to be 43 Hz or higher, to minimize structural interactions with the foot force measurements. The inertial ground frame reference, or ground reaction frame, is constructed from a carbon steel box-tubing welded framework with grouted base pads which accept concrete anchors. Modes of vibration of this structure were found to meet the established criterion, with the first mode in the Z-direction (the longitudinal axis of the runner) at 70 Hz. The treadmill frame, which accommodates treadmill mechanical and electrical components, force plate, and subject load device system, is constructed from an aluminum box-tubing welded framework. The treadmill base mounts to the 1-Degree of Freedom linear translation system via air bearings (described earlier in Section I). This offloads the weight of the treadmill system and allows frictionless movement in the runner's longitudinal axis. The treadmill frame and air bearing assembly modes were also found to be acceptable, with the first mode axial to the runner at 45 Hz.

The initial rigid body model of the exercise system provides a good illustration of one of the effects that the enhanced Zero-gravity Locomotion Simulator is designed to study and serves as a starting point for building more sophisticated models of exercise systems for use in long-duration manned spaceflight. Adding more detail regarding biomechanical simulation of the runner, higher-order treadmill and rack dynamics, and an active subject loading device will greatly enhance the model. The model can then be validated against tests performed on the eZLS in normal earth gravity and modified for use in 6-Degree of Freedom systems in order to simulate performance of crewmember exercise aboard the ISS, or long-duration lunar and Mars exploration missions.

III. Treadmill with Vibration Isolation and Stabilization (TVIS) Harness Comfort Evaluation

The first pilot study completed at the Exercise Countermeasures Laboratory in the context of Space Exploration and the Exercise Countermeasures Project (ECP) mission to develop requirements for new exercise equipment designs, sought to develop a standardized test protocol for evaluating comfort and effectiveness of the International Space Station (ISS) Treadmill with Vibration Isolation and Stabilization (TVIS) harnesses when loading subjects during simulated zero-gravity treadmill exercise. The objective of this pilot study was to develop a harness evaluation test design to evaluate and compare existing harnesses with each other and with future designs as they emerge.

This study considered the exercise harness and Subject Load Device (SLD), which applies loads directly into the harness, as a system of parts which affects comfort. That is, it was hypothesized that the harness system cannot be evaluated in isolation from the SLD system. Therefore the SLD loading characteristics (force-displacement, and % body weight setting), were also included as test variables to be examined in the study.

Currently, there are three harnesses designed for use with the TVIS on-orbit treadmill. These harnesses are; i.) Russian, ii.) U.S. and iii.) a re-designed U.S. harness (Figs. 5A, B, and C). The redesigned U.S. harness was engineered to more closely match the Russian harness based on crew comfort observations. Anecdotal information from crew members indicates that the U.S. harness waist belt is ineffective under loads approaching body weight. The belt slides over the iliac crest once load is applied, transferring the majority of the load bearing responsibility to the shoulders and leading to significant discomfort over the greater trochanter of the hip and the shoulders. Discomfort using the currently-available TVIS harnesses is consistently reported by ISS crew members. It is likely that this discomfort directly impacts the efficacy of the exercise protocols performed. The Foot experiments[4] on the ISS have shown that TVIS exercise using the available harness and SLD has resulted in low ground reaction forces on-orbit (~60% of 1g loads) and is believed to be a factor in the observed loss of bone mineral density in crew members.

The Cleveland Clinic prototype harness design (Fig. 5D), and the ground-based LM-SLD (approaching constant-force loading) were included in the study, as well as the current ISS harness (redesigned U.S. harness based on Russian design) and ISS Series Bungee System.

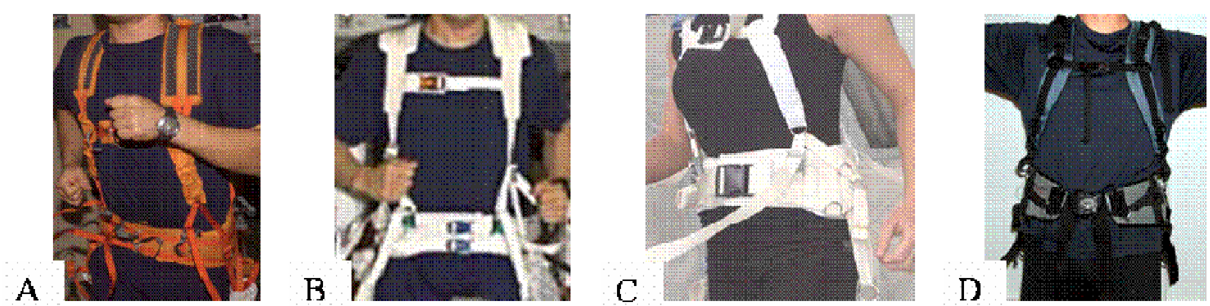


Figure 5. Harnesses used on-orbit and in simulated microgravity. *(A) Current Russian harness in use on the International Space Station (ISS). (B) U.S. harness being used during treadmill exercise on ISS. (C) Re-designed U.S. harness currently in use on ISS and under evaluation by NASA. (D) Cleveland Clinic prototype harness. Harnesses shown in (C) and (D) were evaluated in the pilot study described herein. Photos A-C courtesy NASA. Photo D courtesy The Cleveland Clinic.*

IV. Experimental Methods

A. Study Design

Six test subjects (three male, three female) were approved for participation in the pilot TVIS Harness Comfort study, under approved Institutional Review Board (IRB) protocol from the NASA JSC Committee for the Protection of Human Subjects (CPHS). Test subjects' age ranges were 21-49 years, and were selected to envelop the 5^{th} to 95^{th} percentile range of body heights and weights for the astronaut corps according to NASA STD-3000 Anthropometric Data. Test subjects were screened first for health risks by a registered nurse via a Health History Questionnaire, and given Air Force Class III medical exams. Test subjects who were over age 40 years, or over age 35 years with two risk factors (e.g., family history of heart disease, high cholesterol, high blood pressure) also received a graded treadmill stress-test with electrocardiogram (Bruce Protocol). All data were de-identified in accordance with the approved IRB protocol.

Test subjects exercised with a flight replica of the U.S. harness (currently in use on the International Space Station), and a custom-fit prototype harness (the Cleveland Clinic design), at 7 mph for 3-minute sessions on the eZLS at 50%, 75%, and 100% bodyweight (BW), using two subject load devices – the LM-SLD and flight replica ISS bungees. Subjects also ran for 20 minutes continuously, at 5 mph (slow jog), with each of the two harnesses and the LM-SLD set at 75% BW. Subjects' heart rate was monitored continuously throughout the exercise sessions with a heart monitor (Polar Electro Inc., Lake Success, NY) and wireless transmitter. The maximum allowable heart rate during this study, as dictated by the IRB panel, was 75% of age-predicted maximum, calculated by the formula 220 minus the subject's age in years.

B. Short-Duration Running Trials

Each subject ran a total of 12 trials, each 3 minutes in duration. Subjects were allowed to return to their resting heart rate between trials, and the 3-minute trials were limited to no more than 6 per day. No long-duration trials were performed on the same day. The data collected during this portion of the study included comfort evaluation, ground reaction force, heart rate, contact pressure on the shoulders and SLD in-line load, at 1-minute intervals for 30 seconds at a time during the trial duration.

For effective use of test time and to minimize the number of suspensions/dismounts, subjects were tested with one harness on a given day. One short-duration data collection day per harness met the 6 trials per day limit and simplified the test subject suspension procedures. Only 1 trial was attempted for each % BW and SLD configuration. This is done to limit the overall test duration, and may be a limitation of the study to be addressed in future studies. Each exercise session included subject suspension, warm-up, exercise, cool-down, and subject dismounting. Suspension consisted of donning the harness, a helmet and eight limb supports (two on each limb), followed by lying in a supine position on a suspension cradle on a gurney, connecting the limb supports to the suspension cables and being raised by an overhead lift system. Warm-up consisted of two minutes of walking at 3 mph, followed by three minutes of jogging at 5 mph. Exercise consisted of running at 7 mph under each SLD load of 50, 75 and 100% bodyweight for a 3-minute duration. Subjects were asked to subjectively assess their level of comfort in six categories: hips, neck, shoulders, back, waist, and overall, using a 100 mm Visual Analog Scale (VAS)[6-9]. The VAS consists of a 100 mm horizontal line with inverse descriptors at opposite ends of the scale. The descriptor on the far left was "No Pain" and on the far right was "Worst Imaginable Pain." The subjects were asked to draw a hash mark along the line that corresponded to the pain they felt at the time in each of the six categories. The VAS was administered after suspension, but prior to the exercise session (baseline), after the warm-up, and after each 3-minute trial. For analysis, the VAS ratings were recorded to the nearest millimeter.

The subjective VAS ratings were used in concert with objective pressure measurements at the shoulders. Contact pressure sensor mats (Novel Corporation, Munich, Germany) were used to record pressure readings under the shoulder straps of both harness types. Pressures were recorded with the sensors every minute for 30 seconds during the 3-minute running trials. The recorded data was filtered, averaged over the individual sensors within the mat at each time point and then averaged over the recording period. In addition, the maximum pressure value was found at each time point for each data set and those values were averaged over the recording period.

Cool-down consisted of three minutes of jogging at 5 mph followed by two minutes of walking at 3 mph, and was performed at the discretion of the subject. The dismounting procedure consisted of lowering the subject onto a gurney, disconnecting the subject from the support system and removing the helmet, limb supports and harness.

A 

B 

Figure 6. Test subject equipment close-up detail. *(A) The contact pressure sensors were placed beneath the left and right sides of the harness shoulder straps on top of the subject's clothing and zeroed in place with no load. The sensors measured pressure under the shoulder straps of the harnesses during running trials in the simulator. (B) Prototype harness hip belt showing split feature at iliac crest.*

C. Long-Duration Jogging Trials

Each subject also participated in two jogging trials of 20 minutes each, to assess long-term comfort of the harnesses. Subjects were loaded to 75% bodyweight via the LM-SLD loading system, and jogged at 5 mph. Only one 20-minute run was performed per subject on any given day, with no short-duration trials performed on the same day. A VAS was also administered to the subjects during these long-duration trials. A baseline VAS was administered after suspension but before any exercise, as well as after the warm-up and again after the 20-minute trial. Additional data collected during this portion of the study included heart rate, ground reaction force, contact pressure on the shoulders and SLD in-line load, at 5-minute intervals for 30 seconds at a time during the trial duration.

D. Additional Test Subject Considerations

Test subjects were given a minimum of 2 days of rest between consecutive test sessions. Prior to beginning the next test session, subjects were queried regarding any soreness or discomfort as a result of the previous session. Any reports made by the subjects (e.g., minor brusing, soreness, redness) were reported to the IRB and if possible, causes of the discomfort were remedied (e.g, adding foam underwrap beneath the suspension cuffs at the wrists).

V. Results and Discussion

A. Visual Analog Scale (VAS) Results

The averaged VAS ratings from the short-duration trials at each body location for each harness/SLD combination are plotted against the target % body weight in Figure 7a. These results indicate that the subjects primarily experienced discomfort in the shoulders and mainly with the U.S. harness. There was a slight amount of discomfort in the back with both harnesses and a slight amount of discomfort in the hips with the Cleveland Clinic (CCF) prototype harness. The overall discomfort ratings appeared to mirror those of the shoulders.

The average VAS ratings at each body location for each harness type are plotted for the long-duration trials in Figure 7b. In these trials, discomfort was experienced in the shoulders, neck and back with the U.S. harness, and a relatively small amount of discomfort was experienced in the back and hips with the CCF prototype harness. The magnitudes of the overall ratings were comparable to the ratings at the individual body locations. These results suggest that the U.S. harness was less comfortable than the CCF prototype harness, particularly in the shoulders. However, more data is necessary for conclusive evidence. Due to the safety restrictions preventing the heart rate to be elevated above 75% of the subject's age-predicted maximum, on average only 75% of the running time specified in the protocol for the short-duration trials was completed. In particular, only 2 subjects were able to complete the

100% body weight conditions. Five subjects completed the 75% body weight condition and all six subjects completed the 50% body weight condition. For the long-duration trials, 71% of the running time specified in the protocol was completed. These protocol reductions and the low number of subjects (n=6) participating in study limited the amount of data collected; however, the study aim of establishing a standard test protocol for evaluating crew equipment for comfort was a key success.

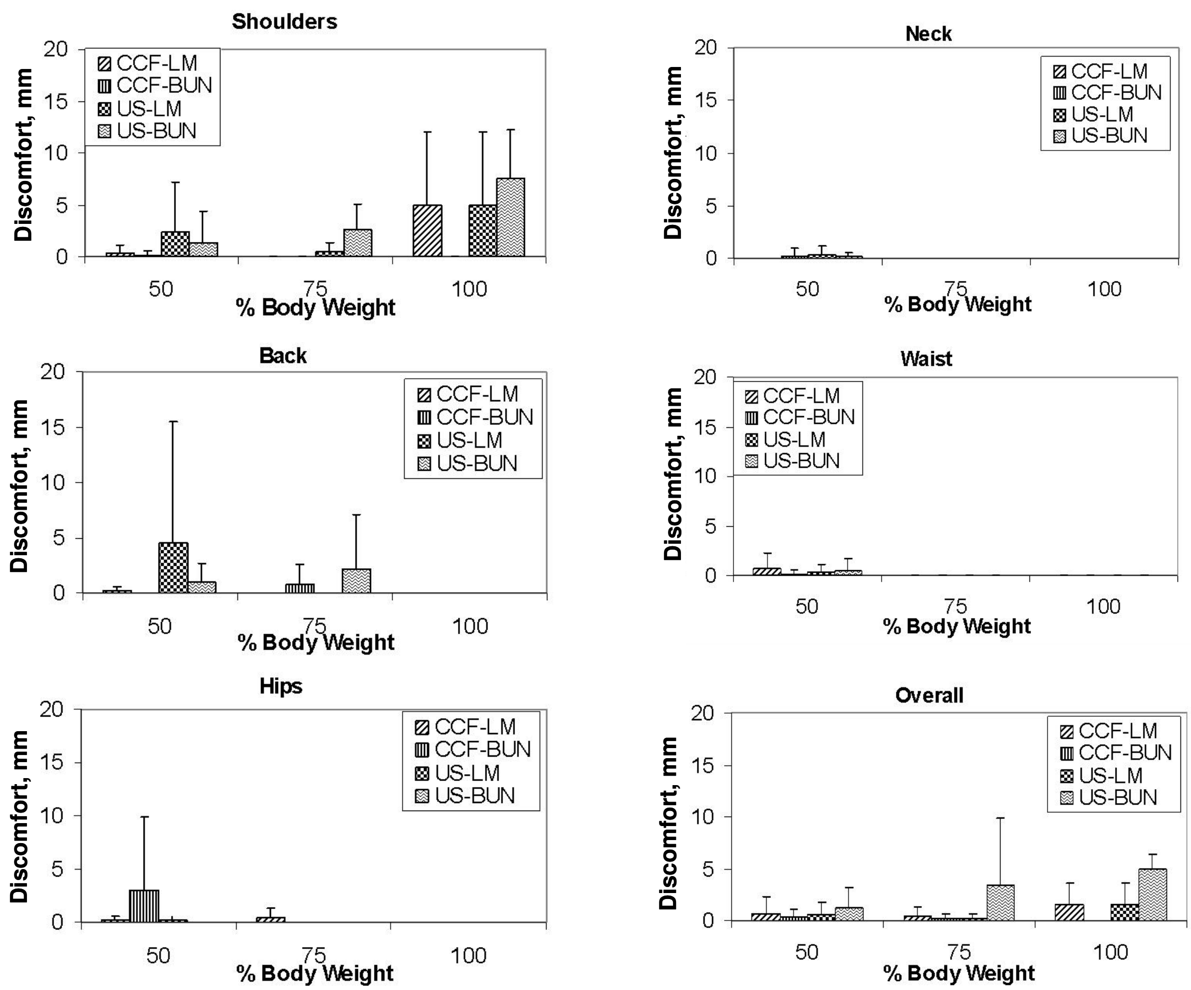


Figure 7a. Visual Analog Scale (VAS) Results – Short-duration trials. *The average Visual Analog Scale (VAS) ratings for the short-duration trials at each body location plotted against the target % body weight for each harness/Subject Load Device (SLD) combinations; Cleveland Clinic harness – Linear Motor SLD (CCF-LM), Cleveland Clinic harness – Bungee SLD (CCF-BUN), U.S. harness – Linear Motor SLD (US-LM), U.S. harness – Bungee SLD (US-BUN).*

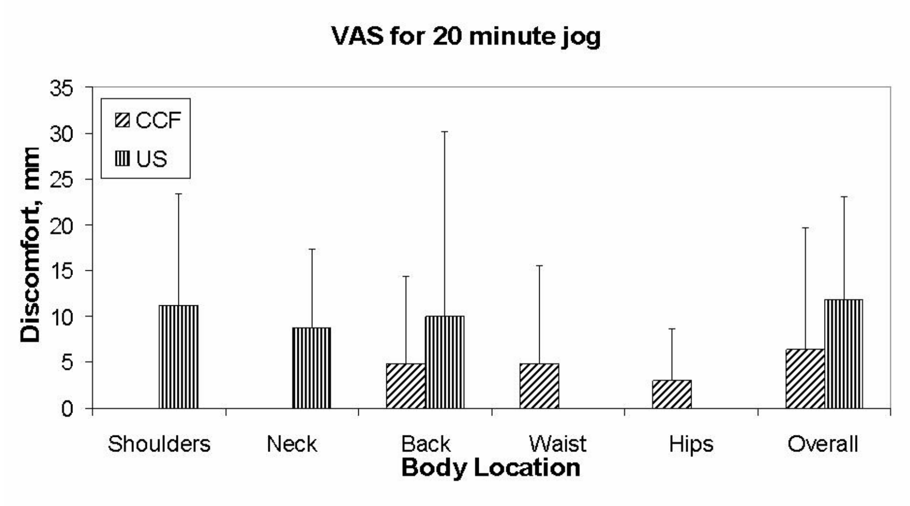


Figure 7b. VAS Results – Long-duration trials. *The average VAS ratings for the long-duration trials (jogging at 5 miles per hour, 75% body weight with the LM-SLD) at each body location for each harness type; Cleveland Clinic harness (CCF), U.S. harness (US).*

B. Subject Loading Device (SLD) Differences

The VAS ratings are plotted to compare only harness type in Fig. 8a, by lumping data from the two subject loading types together. In this figure it becomes more evident that there is an increase in discomfort at the shoulders as the % body weight the subject is loaded to increases.

A plot of VAS ratings comparing only SLD type, with the two harness types lumped together is shown in Fig. 8b. This figure indicates that the subjects found running with the SBS bungees more uncomfortable than with the LM-SLD, at lower body weights. Discomfort was comparable at 100% body weight loading between SLD types. Figure 8c illustrates the difference between the two loading systems. The actual average load that the subject experiences with the LM-SLD more closely compares to the target % body weight loading than does the actual average load provided by the SBS bungees, which is less than the target load. In addition, the error band of the LM-SLD subject loading is less than the error band of the SBS bungees, demonstrating that the LM-SLD provides a more constant force than the ISS bungees. The constant force imparted by the LM-SLD may be the reason for the lower VAS scores when the two loading devices are compared.

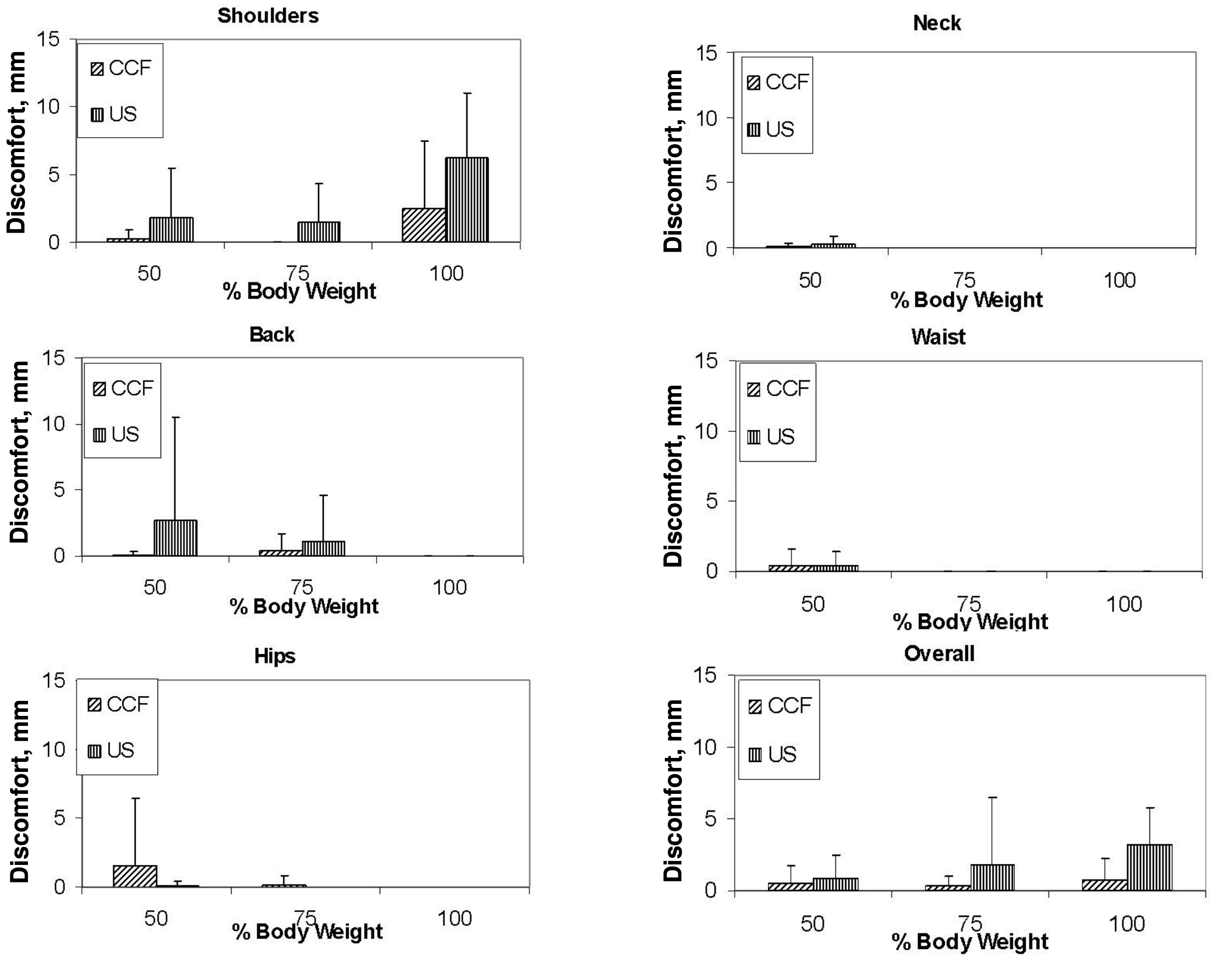


Figure 8a. VAS Results – By harness type. *The average VAS ratings for the short-duration trials at each body location plotted against the target % body weight for each harness type, with SLD loading type lumped together.*

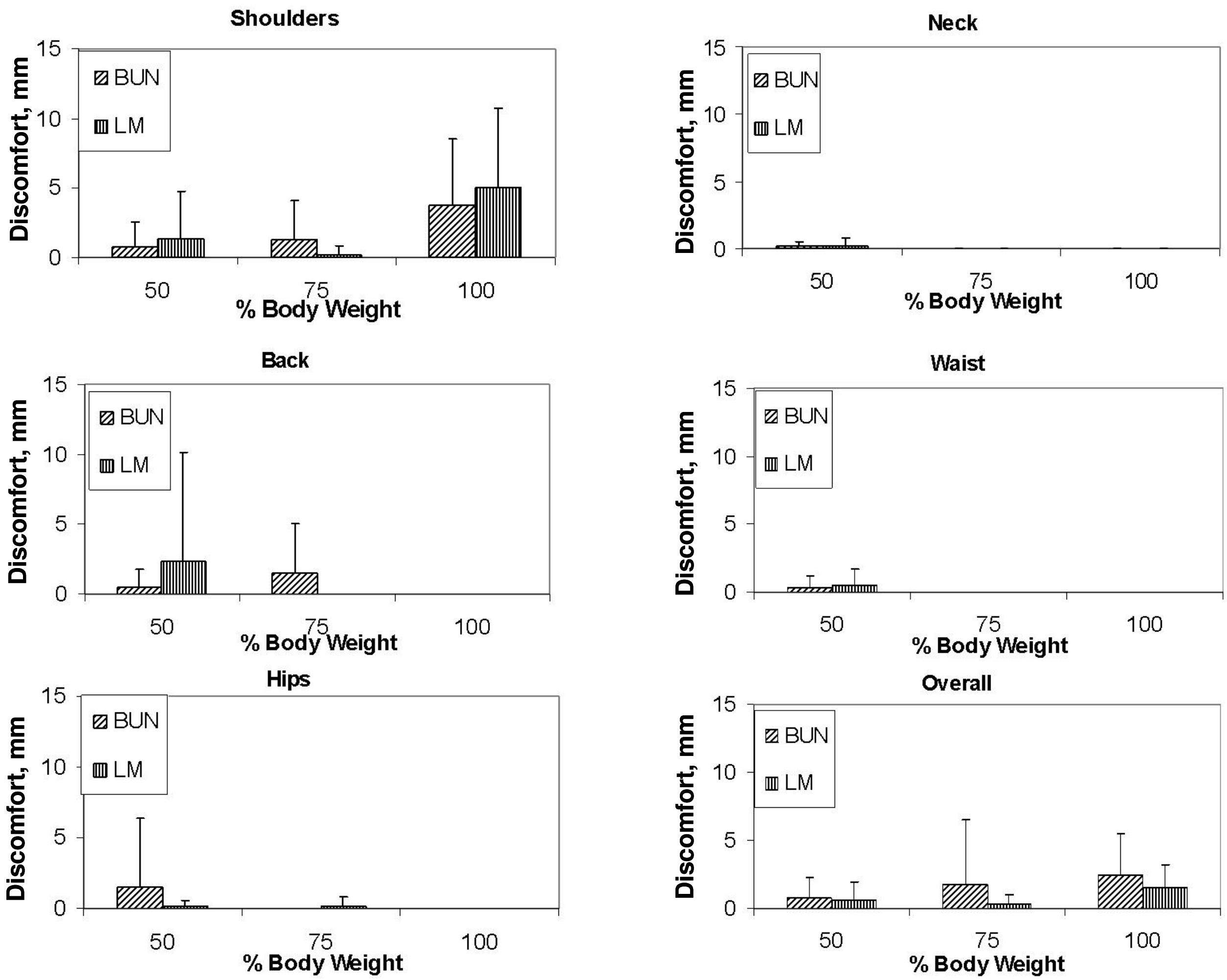


Figure 8b. VAS Results – By SLD type. *The average VAS ratings for the short-duration trials at each body location plotted against the target % body weight for each SLD type; Bungee SLD (BUN), and Linear Motor SLD (LM), with harness type lumped together.*

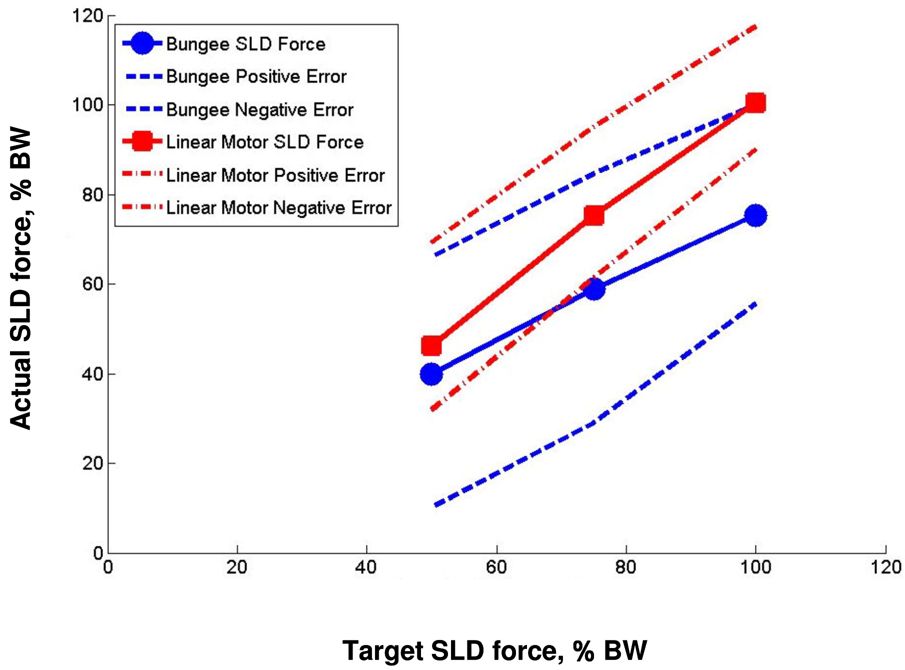


Figure 8c. Differences between SLD types. *The average actual load produced by the SLD type compared to the target subject loading level. Also indicated is the average error introduced by each subject loading device.*

C. Pressures on the Shoulders

We also made comparisons of the mean pressure and maximum pressure experienced between the CCF prototype harness and the U.S. harness as measured by the contact pressure sensor mats, as shown in Fig. 9. The mean pressure and maximum pressures experienced at the shoulders were consistently greater in the U.S. harness than in the CCF prototype harness. This provides additional objective evidence that the CCF prototype harness is effective in reducing the excessive loading experienced at the shoulders as compared with the U.S. harness. These results are consistent with those found with the subjective VAS. The VAS ratings in the shoulders were much higher for the U.S. harness than for the CCF prototype harness. Also, the fact that there was some discomfort reported at the hips in the CCF prototype harness perhaps indicates that this harness may be able to more evenly distribute the loading between the shoulders and hips, whereas the U.S. harness appears to concentrate the loading at the shoulders.

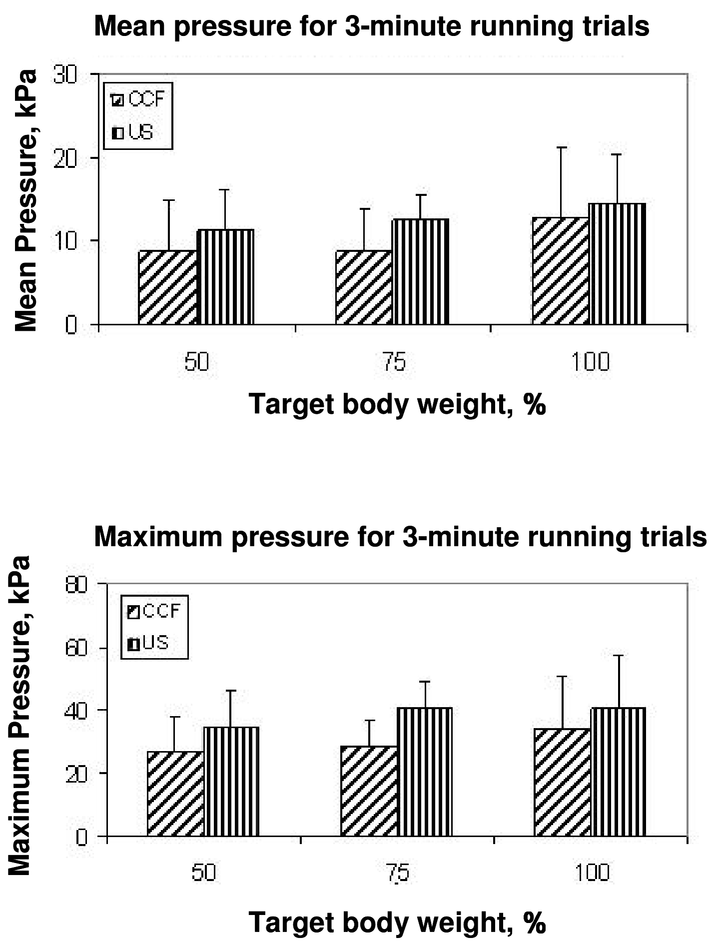


Figure 9. Pressures on the shoulders. *The average and maximum pressures measured in kilopascals (kPa) at the shoulders vs. target body weight for the two harness types; Cleveland Clinic harness (CCF), and U.S. harness (US), measured during the 3-minute running trials.*

VI. Conclusion and Future Studies

In conclusion, we have developed a ground-based analog capability at NASA Glenn Research Center to allow development and evaluation of advanced exercise countermeasures devices, crew equipment, and prescriptions for counteracting the detrimental physiological effects of long-duration spaceflight. The research study described herein is the first of a series of experiments planned to help address these issues. While the current pilot study was not designed to be able to determine with statistical significance which crew harness/loading combinations were most comfortable, the data suggest, however, that the Cleveland Clinic prototype harness holds promise for future development for flight applications. Specific focused experiments can be designed to establish statistical significance on this harness combination or improved concept harness designs. A further experiment might be designed to show what increased comfort might provide in terms of the workout routine; for example, can test subjects comfortably run for longer durations or at a higher loading with the improved harness?

Aside from space applications, experiments conducted using the eZLS may help medical researchers develop methods to help prevent osteoporosis in the terrestrial population as well, as the mechanism of bone and muscle loss is very similar, though greatly accelerated during space travel. The eZLS will be used as a ground-based testbed to support future missions for space exploration and will eventually be used to simulate planetary locomotion in partial gravity environments including the Moon and Mars.

The Exercise Countermeasures Laboratory and the enhanced Zero-g Locomotion Simulator provides a unique set of capabilities for simulating interfaces to the vehicle which will affect the degree to which the body is loaded in space, and for simulating partial gravity environments for planetary surface applications. Future studies will examine muscle activation patterns and joint kinematics during locomotion in the simulator and during upright running on a standard treadmill, as compared with locomotion in true microgravity, effects of varying compliance on force-generation capability of exercise devices designed for use in space, and assessing physiological demand (e.g., heart rate, oxygen consumption) during locomotion in simulated lunar gravity.

Acknowledgments

The authors wish to acknowledge Donald Ahrens, John Bednarek, Ton van den Bogert, Brian Davis, Ricki Englehaupt, Kerim Genc, and Andrea Rice (Cleveland Clinic, Center for Space Medicine); Alan Chmiel, Carlos Grodsinsky, Brad Humphreys, David Root, Mike Rossiter, Sergey Samorezov, Mark Savina, Christopher Sheehan, (Zin Technologies); Scott Cutlip, Thomas Goodnight, Gary Gorecki, Daniel Haas, Richard Manella, Nelson Morales, Miguel Polanco, and Christopher Williams (NASA Glenn Research Center); Renita Fincke, Dave Francisco, and Linda Loerch (NASA Johnson Space Center), for their support and dedication to the implementation of the Exercise Countermeasures Laboratory and enhanced Zero-g Locomotion Simulator at NASA Glenn Research Center. This work is sponsored by the Exercise Countermeasures Project at NASA Johnson Space Center, and is funded in part by the National Space Biomedical Research Institute grant BL00402 through NASA NCC 9-58.

References

[1]Davis B.L., Cavanagh P.R., Sommer H.J., III, and Wu G., “Ground reaction forces during locomotion in simulated microgravity.” *Aviation, Space and Environmental Medicine.* Vol. 67, No. 3, 1996, pp. 235-242.

[2]Hewes, D.E., “Reduced gravity simulators for studies of man’s mobility in space and on the moon.” *Human Factors,* Vol. 11**,** 1969, pp. 419-432.

[3]Cavanagh, P.R., Polliner, J., and Davis, B.L., “Design principles for a zero gravity locomotion simulator.” *Proceedings of XIIth International Congress of Biomechanics*. International Society of Biomechanics. University Park, PA, p. 434.

[4]Cavanagh P.R., Maender C., Rice A.J., Genc K.O., Ochia R.S., and Snedeker J.G., “Lower-Extremity Loading During Exercise on the International Space Station.” *Transactions of the Annual Meeting of the Orthopaedic Research Society*. 2004, p. 395.

[5]Kram, R., Griffin T.M., Donelan J.M., and Chang Y.H., **“**Force treadmill for measuring vertical and horizontal ground reaction forces.” *Journal of Applied Physiology* Vol. 85, Issue 2, 1998, pp. 764-769.

[6]Thomeé R., Grimby G., Wright B.D., and Linacre J.M., “Rasch analysis of Visual Analog Scale measurements before and after treatment of patellofemoral pain syndrome in women.” *Scandinavian Journal of Rehabilitation Medicine* Vol. 27, 1995, pp. 145-151.

[7]Bijur, P.E., Silver W., Gallagher E.J., “Reliability of the visual analog scale for measurement of acute pain.” *Academic Emergency Medicine*, Vol. 8, 2001, pp. 1153-1157.

[8]Jacobson, B.H., Book, D.A., Altena, T.S., Gemmell, H.A., and Hays, B.M. “Comparison of perceived comfort differences between standard and experimental load carriage systems.” *Ergonomics*, Vol. 46, 2003, pp. 1035-1041.

[9]Kirk, J. and Schneider, D.A. “Physiological and perceptual responses to lead carrying in female subjects using internal and external frame backpacks.” *Ergonomics*, Vol. 35, 1992, pp. 445-455.